An Integrated Environmental and Health Performance Quantification

Model for Pre-occupancy Phase of Buildings in China

Abstract: To comprehensively pre-evaluate the damages to both the environment and human health due to construction activities in China, this paper presents an integrated building environmental and health performance (EHP) assessment model based on the Building Environmental Performance Analysis System (BEPAS) and the Building Health Impact Analysis System (BHIAS) models and offers a new inventory data estimation method. The new model follows the life cycle assessment (LCA) framework and the inventory analysis step involves bill of quantity (BOQ) data collection, consumption data formation, and environmental profile transformation. The consumption data are derived from engineering drawings and quotas to conduct the assessment before construction for pre-evaluation. The new model classifies building impacts into three safeguard areas: ecosystems, natural resources and human health. Thus, this model considers environmental impacts as well as damage to human wellbeing. The monetization approach, distance-to-target method and panel method are considered as optional weighting approaches. Finally, nine residential buildings of different structural types are taken as case studies to test the operability of the integrated model through application. The results indicate that the new model can effectively pre-evaluate building EHP and the structure type significantly affects the performance of residential buildings.

Keywords: environmental and health performance (EHP); integrated model; building performance quantification; pre-occupancy phase

1. Introduction

Construction products contribute considerably to total energy consumption and also release considerable emissions to the environment, thus significantly damaging the natural environment and human health. Annual construction in China is expected to reach 2 billion square meters in the coming years as a result of high urbanization rates (55% in 2020) and rapid urban population growth (20 million annually) (Fang, 2009; Zhou, 2010). Buildings have become a major focus of attention in the recent age of sustainability in Chinese society. To scientifically identify major environmental impact factors and to effectively propose improvement measures, building environmental impact assessment (EIA) is necessary.

Life cycle assessment (LCA) methods are regarded as tools that help integrate environmental considerations with product development (Germani et al., 2004; Jeswiet and Hauschild, 2005; Wang, 2009). The LCA concept was first proposed by the Society for Environmental Toxicology and Chemistry (SETAC) in the 1990s. According to the International Organization for Standardization (ISO), the LCA framework involves four steps: goal & scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment, and interpretation (ISO, 2006), as shown in Fig. 1. Several mature evaluation systems based on LCA were developed worldwide over the past several decades. Eco-indicator 99 (EI99) is a damage-oriented approach and

was commissioned as part of the Integrated Product Policy by the Dutch Ministry of Housing, Spatial Planning and the Environment (Goedkoop and Spriensma, 2000). EI99 classifies 11 environmental impact categories into 3 safeguard areas: human health, natural and manmade environments, and natural resources. Moreover, EI99 has proven to be a useful tool for designers to aggregate LCA results into user-friendly units. Environmental priority strategies (EPS), developed by the Centre for Environmental Assessment of Products and Material Systems, is an effective tool for a company's internal product development process (Steen, 1999). This system was created in a top-down manner, and it allocates 18 impact categories into 5 safeguard areas: human health, production capacity of ecosystems, abiotic stock resource indicators, bio-diversity impact indicators, and cultural and recreation value indicators. Impact 2002 links life cycle inventories (elementary flows and other interventions) via 14 midpoint categories to 4 damage categories: human health, ecosystem quality, climate change and resources (Jolliet et al., 2003). These models follow the LCA framework and have been tested through wide application to different products. In addition, there are many other LCA methods, such as CalTOX (USA), Envest (England), and CML2002 (the Netherlands).

Fig. 1. LCA framework.

For buildings specifically, there are several relevant international projects, such as the European Thematic Network on Practical Recommendations for Sustainable Construction (PRESCO) (Peuportier et al., 2005), Energy Related Environmental Impact of Buildings (IEA Annex 31, 2005), and Building Environmental Quality for Sustainability through Time (BEQUEST, 2000). The numbers of building EIA tools are increasing all over the world, and many studies compare the tools themselves or the results from different tools (Forsberg and Von Malmborg, 2004; Haapio and Viitaniemi, 2008; Kawazu et al., 2005; Todd et al., 2001). Building for Environmental and Economic Sustainability (BEES) is supported by the U.S. Environmental Protection Agency Environmentally Preferable Purchasing Program; it measures the building environmental performance during raw material acquisition, manufacturing, transportation, installation, use, and waste management by synthesizing the environmental and economic results into a single score (Lippiatt, 2007). “Optimization of global demands in terms of costs, energy and environment within an

integrated planning process” (OGIP) is designed for the integrated planning of buildings (Kellenberger and Althaus, 2009; Peuportier et al., 2005); it calculates the environmental impact in the construction and operation phases and helps designers to portray the complex relationships between costs, energy and environmental impact. EcoQuantum was developed by IVAM in the Netherlands and classifies the environmental performance of a building into 11 impact categories (EcoQuantum; Peuportier et al., 2005). These building assessment tools are mature but cannot be directly applied to Chinese buildings because the parameter values of environmental impact potentials applied in the characterization, normalization and weighting steps in the EIA are highly depended on the actual environmental loads of the pollutants discharge area (Yang, 2002). Besides, constructions in different countries varies due to climatic and geographic conditions, raw material qualities, economic data, material manufacturing technologies, fuel structures, energy tariffs, labor and many other factors (Dixit et al., 2010). Thus, it is necessary and valuable to develop a building EIA system adopting parameters according to Chinese resources and environment conditions.

To promote building sustainability in China, several studies have been done by the Chinese government and researches in the past decades. The General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ) and the Standardization Administration of the People's Republic of China (SAC) issued two national LCA standards (GB/T 24040-2008 and

GB/T 24044-2008) to guide the LCA of Chinese products (AQSIQ and SAC, 2008a, 2008b). These two voluntary standards are sourced from ISO 14040 and ISO 14044 and support the development of building impact evaluation methods. The Building Environmental Load Evaluation System (BELES) conducts building EIAs based on the endpoint damage oriented approach (Gu et al., 2008a); it classifies impacts into 8 midpoint categories and then allocates them into 4 endpoints: resource exhaustion, energy exhaustion, human health damage and ecosystem damage. The inventory data are gathered from many different studies or estimated based on data from other countries, which decreases the accuracy of the results. Furthermore, BELES uses the panel method to calculate weightings, so the results are inevitably subjective. The Life Cycle Green Cost Assessment (LCGCA) combines LCA with life cycle costing to convert the building's environmental loads to environmental costs based on the trading price of carbon dioxide (CO₂) certified emission reductions (Gu et al., 2008b). However, this model relies heavily on environmental policies and environmental tax mechanisms, which are far from sound in China. In addition, LCGCA is only suitable for projects in which costs are paid by the same party throughout the whole life cycle. The Building Environmental Performance Analysis System (BEPAS) is a premium system funded by the Ministry of Housing and Urban-Rural Development (MOHURD) (Zhang et al., 2006) that has served as a methodological base for the construction industry standard in China – the *Standard for Sustainability Assessment of Building Project* (MOHURD, 2011). BEPAS allocates building environmental

impacts into ecological damage and resource depletion, and then into many sub-categories. The Building Health Impact Assessment System (BHIAS) (Kong, 2010) was developed based on EPS to quantify damages to human health in the life cycle of buildings. It follows the LCA framework and uses willingness to pay (WTP) as the weighting method. BEPAS and BHIAS are relatively mature models in China, and their reliability and operability have been tested through many project applications.

To better apply BEPAS and BHIAS on a larger scale and to improve green construction in China, two limitations should be addressed. First, these two models allocate impacts into different categories, causing problems for comprehensively assessing building environmental and health performance (EHP). Buildings have negative impacts on ecosystems, natural resources and human health, and people are concerned about these effects. An integrated assessment model that covers all these categories will help to scientifically identify major EHP factors and propose effective improvements. Second, in previous studies, these two models serve as post-construction assessment tools to accept the completed work instead of as pre-evaluation tools (Li et al., 2010). The consumption data in previous studies are derived from actual measurements and can only be retrieved after the project is completed. This data collection method limits the practical value of the assessment results. To address the above gaps, the authors proposed a conceptual framework (Li et al., 2014a); however, more details and information, such as the complete

assessment approach and flow, data conversion mode, and available weighting methods, should be examined.

Following the LCA framework, this study integrates BEPAS and BHIAS into a new model to quantify combined EHP for buildings. The new assessment model uses engineering quota to acquire the consumption data, and the impacts considered cover three common safeguard areas: ecosystems, natural resources and human health. Nine residential buildings are taken as case studies to illustrate how the model works and to validate its feasibility.

2. Base models and the feasibility of their integration

BEPAS is a premium system funded by MOHURD and has been served as the foundation of the *Standard for the Sustainability Assessment of Building Projects*. This system quantifies environmental impacts in three aspects that are closely related to environmental performance: building facilities, building materials and location. Then, BEPAS allocates the impacts into two safeguard areas (ecosystems and natural resources) and 11 impact categories. The social WTP approach is used to quantify the relative severity levels across different impact categories, and the weighting factors are proposed based on the concept of green taxes that are levied on emissions and natural resources (Wu et al., 2005). Finally, all impacts are integrated into a single value: the eco-point. The larger the eco-point is, the more serious the environmental impacts are. For more detailed information, please refer to Zhang et al. (2006).

BHIAS is developed to quantify the damage to human health in building life

cycle based on LCA principles and EPS. This system establishes a causal relationship between environmental pollutants and negative effects to human health to quantify the degree to which construction activities affect human wellbeing. BHIAS classifies health impacts into four sub-categories: global warming-related diseases, respiratory effects, circulatory effects and carcinogenesis. The links between emissions and consequent damages are then established using the influence path method. The disability-adjusted life year (DALY) is used to determine the negative effects of disease incidences and to transform the inventory analysis results into monetization loss values. For more detailed information, please refer to Kong (2010).

The new model integrates the inventory analysis, classification, characterization, and weighting steps of BEPAS and BHIAS to perform a comprehensive EHP assessment. These two models can be integrated into a single model for the following reasons:

- By their nature, both BEPAS and BHIAS are LCA-based assessment approaches that adhere to the cause-effect chain analytical pathway and follow the framework shown in Fig. 1. This intrinsic consistency lays a solid foundation for integrating the models.
- The transformation paths from impact categories to related safeguard areas in BEPAS and BHIAS are quite different. BEPAS applies category indicators and equivalent units to conduct characterization and then allocates the impacts into ecological damage and resource depletion. In contrast, BHIAS uses the influence

path method to transform emissions into consequent potential damages and expresses the health quantification results using DALY (for more detailed information, please see section 3.3). However, BEPAS and BHIAS both focus on some key pollutants, such as CO₂, sulfur dioxide (SO₂), nitric oxide (NO_x), and dust, and share an input-output database. Moreover, the different categories in the two models are aggregated into a unified unit through the weighting step, which expresses the different evaluation results across various categories as a single value. The unified input data and output expressions make the integration feasible.

- Both models are open systems; thus, more emitted pollutants and consumed resources are considered in BEPAS, and more diseases due to construction can be added to BHIAS with the development of related researches. This open structure supports integration across different categories and also provides the potential to improve the comprehensive assessment model.

3. Integrated model framework

Based on BEPAS and BHIAS, an integrated model was developed to quantify building EHP. The new model framework is shown in Fig. 2, and its four steps are introduced below.

Fig. 2. Integrated assessment model framework.

3.1 Scope definition

The scope definition step provides specific boundaries for the evaluation. The building life cycle spans “from the cradle to grave,” including planning, design, raw material extraction and manufacture, transportation, on-site construction and installation, operation and maintenance, and demolition (see Fig. 3). Unlike conventional “total LCA,” this paper conducts a “partial LCA” and excludes certain environmental impacts from analysis similar to many other building EIA studies (Hammond and Jones, 2008; Hernandez and Kenny, 2010; Monahan and Powell, 2011). The assessment boundary in this study covers extraction and manufacture of raw materials, transportation of building materials and components, on-site construction and installation, which is collectively referred as the pre-occupancy phase, as shown in Fig. 3. The pre-occupancy phase is very important for alleviating the current environmental pressure, and the environment impacts in this phase were assessed with LCA models in the past few years (Heinonen et al., 2016; Li et al., 2015; Luo et al., 2016). In particular, the energy consumed in the pre-occupancy phase is a hot topic studied by researchers all over the world (Chang et al., 2010, 2011; Chen et al., 2001; Ciravoglu and Taygun, 2013; Dixit et al., 2010; Doh and Panuwatwanich, 2014; Reddy and Jagadish, 2003).

The planning and design phases are not included in the boundary because these activities are professional work that has no impacts on environment or human health. The operation phase is excluded even though its activities have the greatest impact (75-90% of the total energy consumption) (Jang et al., 2015) due to the following considerations:

- This model is designed to comprehensively evaluate construction impacts and to scientifically offer improvement measures. The pre-occupancy phase is the physical formation of a building

involving a value chain of entities (e.g., building material suppliers, mining contractors, manufacturers and construction contractors). Effective and specific improvement measures based on the evaluation results can be adopted by these entities to promote green building development.

- The operation phase is quite long, and the related pollutions are emitted over the next few decades. Most of the current evaluations use static models and ignore the time values, which is widely criticized for incorrectly estimating the results (de Faria et al., 2015; Filleti et al., 2014; Levasseur et al., 2010; Ness et al., 2007; Reap et al., 2006). Some studies discounted the future impacts (Levasseur et al., 2010), but this method is very controversial (Hellweg et al., 2003; O'Hare et al., 2009). Unlike the operation phase, the pre-occupancy phase is quite short, and its impacts are more intensive. Neglecting the time value has only a small influence on the high reliability of the assessment results.
- With the growing interest in sustainable buildings, the accumulated EHP in the pre-occupancy phase will become more important. The energy use in the pre-occupancy phase has been increasing for energy efficiency buildings (Sartori and Hestnes, 2007) and makes up a considerable part of the total energy use in low energy buildings (Thormark, 2002). Moreover, there are numerous on-going construction projects every year in China due to the rapid process of industrialization and urbanization (Chang et al., 2013). Therefore, the assessed impacts in the pre-occupancy phase help to offer feedback on structure selection, project design and scheme optimization and to reduce environmental burdens (Jang et al., 2015).

Fig. 3. Life cycle of a building.

3.2 Inventory analysis

Inventory data refer to the raw materials and energy required to realize functions and the consequential pollutant emissions in one functional unit (AQSIQ and SAC, 2008b). The functional unit is a reference unit that satisfies the major functions of a system, providing a common basis for comparison (Corsten et al., 2013; Frenette et al., 2010). Per unit floor area (1 m²) is taken as the functional unit in this model. Inventory analysis involves three steps: bill of quantity (BOQ) data collection, consumption data formation, and environmental profile transformation.

(1) BOQ data collection based on work breakdown

BOQ is a document that itemizes the materials, parts and labor of a project, reflecting the comprehensive construction workload. From the system perspective, a construction project can be

viewed as an assembly of several work items and unit processes (Li et al., 2010). It is necessary to systematically decompose the project into detailed unit processes to fully identify the engineering quantities of construction activities. Referring to the previous study (Li et al., 2014b), this paper applies the work breakdown structure (WBS) concept and the national standard (*Code of Valuation with Bill Quantity of Construction Works*) to decompose the construction process into permanent work and temporary work and then into 11 smaller unit processes, as shown in Fig. 4. This breakdown method ensures that the unit processes and input-output data are complete and that the inputs and outputs of energy, resources and pollutants are relatively convenient to measure, making it feasible to apply the methodology to assess the building EHP and to compare different construction projects.

Fig. 4. Unit process division of a construction project (Li et al., 2014b)

(2) Consumption data identification based on engineering quotas

The BOQ data provides engineering quantities of each unit process but fails to offer adequate details of building materials and equipment consumption (Li et al., 2014b). In this proposed model,

we use estimated data retrieved from engineering drawings and quotas to realize consumption predictions. The first engineering quota in China is the *National Unified Engineering Quota for Construction Projects (GJD-101-95)* published by MOHURD in 1995 (MOHURD, 1995). In recent years, engineering quotas in provinces have been developed and updated according to the various building sector performances and improving construction technologies. Engineering quotas refer to the standard number of laborers, machines and materials used in construction works to complete one qualified unit product under current construction conditions (Sun et al., 2009). These quotas can reflect a specific quantitative relationship between qualified engineering products and various related forms of production consumption for average construction industry levels rather than specific technical and management levels of certain contractors. Moreover, this data acquisition method is able to forecast building consumption at the design phase before construction starts. Engineering quotas transform the engineering quantities of unit processes into consumption data of building materials and equipment (as listed below) to meet the requirements of inventory analysis. The simple conversion relationships and losses incurred during implementation (i.e., transportation, construction and site stacking) are also considered because they occupy a certain proportion of the overall consumption.

- building material data (e.g., the quantities of concrete, polyvinyl chloride, and cement);
- mechanical equipment data (e.g., the consumption of water, electricity and diesel for running equipment);
- support items data (e.g., the quantities of formwork, scaffolding, and temporary field road construction); and

- building material losses (e.g., the losses of concrete, steel, and cement).

(3) Environmental profile transformation based on input-output databases

This step involves transforming the consumption of materials and energy into environmental profiles (consumed resources and discharged emissions). The key is a set of comparatively complete inventory databases that includes inputs (materials and energy) and outputs (pollutions) related to the functional unit. Many research projects have worked on collecting and offering inventory databases for LCA studies, and ecoinvent (SimaPro) is a widely used one. ecoinvent was funded by the Swiss Centre for Life Cycle Inventories (Ecoinvent Centre; Weidema et al., 2013) and includes LCI datasets in the areas of energy supply, agriculture, transport, construction materials, and metals processing. In the last several decades, ecoinvent has been applied in many building EIA studies (Blengini and Carlo, 2010a, 2010b; Bribián et al., 2011; Passer et al., 2007, 2012).

eBalance and the Chinese Life Cycle Database (CLCD) were developed to support inventory analysis especially for Chinese products. eBalance is a professional LCA analysis software developed based on the site-specific characteristics of China and has been adopted by more than 1000 users from China and around the world (Sichuan University; Liu et al., 2010). It is powered by high-quality life cycle databases worldwide, including CLCD, the European Reference Life Cycle Database, and the ecoinvent database. The CLCD database represents the Chinese market average technology and [production characteristic](#) with more than 600 datasets, and it is still expanding. CLCD includes the inventory data of energy consumption, water consumption, mineral resource consumption, greenhouse gases (GHGs), acidification, eutrophication, etc. and nearly 200 consumed

resources (e.g. crude coal, natural gas, iron, zinc, and fluorite) and 1000 discharged emissions (e.g. sulfur hexafluoride, phosphorus pentoxide, chemical oxygen demand, sulfur trioxide, benzene). This database has been widely used and tested in the LCAs of Chinese products, such as tillage systems (Xue et al., 2014), ceramic façade materials (Han et al., 2015), household garbage (Lei et al., 2014), residential buildings (Liu and He, 2015), and railway transportation (Yang et al., 2013). Considering the complete database, sufficient elementary flows and site-specific characteristics, this study uses eBalance software and the CLCD database to conduct inventory analysis.

3.3 Impact assessment

(1) Classification

Classification is a process that assigns different inputs and outputs to selected impact categories. We divide impacts into three widely accepted safeguard areas (i.e., ecosystems, natural resources and human health) and then into several detailed categories to cover the major areas to which people pay attention. The considered categories of ecological damage and resource depletion refer to the BEPAS model (e.g., global warming, photochemical smog, eutrophication, solid waste, and water resource depletion) (Li et al., 2010; Zhang et al., 2006), and the categories of human health damage are global warming-related diseases, respiratory effects and circulatory effects referring to BHIAS with the discharge of pollutants in pre-occupancy phase into consideration (Kong, 2010).

(2) Characterization

Characterization quantifies the relative contributions of each input-output to its assigned

category. This step is critical because several pollutants can have similar effects, e.g., SO₂, NO_x and ammonia (NH₃) lead to acidification, while SO₂, nitrogen dioxide (NO₂) and particles with diameters of 10 µm or less (PM₁₀) cause respiratory damage. The characterization processes of categories in the three safeguard areas are quite different.

For the ecological damage and resource depletion categories, characterization involves selecting a representative pollutant as a category indicator and its parameter as an equivalent unit to measure the impact potential of other pollutants. For example, global warming potential (GWP) is commonly used as the global warming characterization factor; it indicates the cumulative radiative forcing value caused by a unit of given GHGs relative to the equivalent value for CO₂ in a specified time horizon (Levasseur et al., 2010; Yang and Chen, 2014). The characterization factors of ecological damage and resource depletion categories in this model are identified by the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al., 2007), the World Meteorological Organization and Yang (Yang et al., 2001; Yang, 2002). Table 1 summarizes the calculation formulas to present the characterization step in ecological damage and resource depletion assessment.

Table 1 The characterization formulas of ecological damage and resource depletion (MOHURD, 2011; Zhang et al., 2006)

Category	Formula	Parameter definition
Ecological Damage	$EDi = Mj \cdot Pij$	EDi is the characterization factor value of ecological damage impact category i ; Mj is the mass of pollutant j ; Pij is the impact potential for pollutant j 's contribution to impact category i .
Resource Depletion	$RD = iVci - Vr$	RD is the characterization factor value of water resource; Vci is the water consumption in the unit process i ; Vr is the reclaimed water capacity.
	$RD_{fossil\ energy} = iMi \cdot \lambda i$	$RD_{fossil\ energy}$ is the consumption of fossil energy resource in the unit of kgeq.SCE ^a ; Mi is the

mass of pollutant i ; λ_i is the conversion coefficient of energy i .

^a SCE is the abbreviation of standard coal equivalent.

For human health categories, characterization transforms the incidence cases of each category into DALY based on environmental toxicology and epidemiological studies. DALY was first presented in the World Development Report (World Bank, 1993) and considers not only life time lost but also the disability-adjusted life years. The transformation of pollutions to DALY depends on three intermediate processes: fate analysis, effect analysis and damage analysis based on environmental pathology, as shown in Table 2. More detailed characterization formulas and corresponding values of each damage category are summarized in Supplementary Tables, and all used values are defined according to the climatic, geographic and economic conditions in China.

Table 2 The processes of human health damage characterization step (Kong, 2010)

Process	Formula	Parameter definition
Fate analysis	$C_i = F_i \cdot M_i$	C_i is the increase concentration of pollutant i in impacted area; M_i is the mass of pollutant emission i ; F_i is the fate factor of pollutant i .
Effect analysis	$T_{ij} = E_{ij} \cdot C_i$	T_{ij} is the number of incidence cases of endpoint j in the impacted area caused by pollutant i per year. E_{ij} is the effect factor, the increase incidence cases of endpoint j caused by $1 \mu\text{g} \cdot \text{m}^{-3}$ increase of pollutant i .
Damage analysis	$HD_{ij} = T_{ij} \cdot DALY_j$ $= T_{ij} \cdot (YLL_j + YLD_j)$	HD_{ij} is the characterization factor value of health damage of endpoint j caused by pollutant i per year; $DALY_j$ is the Disability Adjusted Life Years per incidence case of endpoint j ; YLL_j is the Years of Life Lost per incidence case of endpoint j ; YLD_j is the Years of Life with Disability per incidence case of endpoint j .

(3) Valuation

The valuation step integrates the characterized environmental impacts expressed in different units into a single index with weighting factors to support comparisons and decision making (Ji and Hong, 2016), as shown in Table 3. Monetization, distance-to-target and panel methods are three common quantitative weighting approaches (Gu et al., 2008a; Ji and Hong, 2016).

Table 3 The valuation step of impact categories (MOHURD, 2011; Zhang et al., 2006)

Category	Formula	Parameter definition
Ecological Damage	$EI = \sum_i EI_i = \sum_i ED_i \cdot WFi$	EI_i is environmental impact value of impact category i ; WFi is the weighting factor of impact category i .
Resource Depletion	$RI = \sum_i RI_i = \sum_i RD_i \cdot WFi$	RI_i is resource depletion impact value of impact category i
Health Damage	$HI = \sum_i HI_i = \sum_i HD_i \cdot WFi$	HI_i is health impact value of impact category i .

The monetization method is derived from the notion that seriousness can be measured by economic values, and the contingent valuation method, hedonic pricing method and WTP are common examples. WTP is widely used based on the principle that anyone who emits pollutants or consumes natural resources should pay proprietors for using the environment. This approach has been applied in many LCA models: EPS, BEPAS, and BHIAS. The monetization approach offers economic perspectives on a building's environmental impacts and is characterized by its objectivity. However, this approach is controversial. The weighting factors of ecological damage categories and resource depletion categories were proposed based on the concept of green taxes that are levied on emissions and natural resources (Wu et al., 2005). Due to the incomplete green taxation systems in China, previous studies took actual social losses distributed to each kilogram of carbon as an alternative, reducing the objectiveness of the results (Kong, 2010; Zhang et al., 2006). The weighting

factor of human health damage is usually quantified by the value of a statistical life (VSL), which varies with country, age, risk preference, baseline health, and calculation method (Aldy and Viscusi, 2007; Dockins et al., 2004; Smith et al., 2004; World Health Organization [WHO], 2013). This method has been criticized for its various uncertainty sources (Boesch et al., 2008) and because it defines the price of a human life based on the notion that a human life is a commodity that can be traded (Ackerman and Heinzerling, 2005). However, VSL is commonly used in policy and project valuation conducted by governments and regional and international bodies, including WHO, the European Community, the Organization for Economic Cooperation and Development and the World Bank (WHO, 2013).

The distance-to-target approach measures weight using the ratio of the current burden to the future target value (Weiss et al., 2007). The weighting value is higher when the current level is farther from the standard level. The distance-to-target approach focuses on the extent to which society has thus far failed to meet environmental standards (Powell et al., 1997), and it has been applied in Ecoscarcity, EDIP (Wenzel et al., 2000) and some studies (Li et al., 2015; Weiss et al., 2007). Some researchers (Powell et al., 1997) have raised concerns that the emission standards applied in this approach can be based on politics rather than science. Moreover, the evaluation results only reveal the inner-seriousness of a category rather than levels of inter-seriousness across categories. However, advocates of this method argue that the approach is relevant when applied to large developing countries such as China, as weights based on policies can best represent the public consensus. Therefore, the evaluation results can effectively address environmental priorities and offer clear implications for practice (Lin et al., 2005).

For the panel method, independent experts specializing in the evaluation field are asked to arrive at conclusions and recommendations through consensus. As an example, the Delphi method requires experts to complete questionnaires over several rounds. After each round, an anonymous summary of the previous round is provided to experts, and they are encouraged to revise earlier answers referring to the responses of other members. After several rounds, the range of answers decreases, and the experts converge to the “correct” answer. This weighting method has been used successfully in BELES (Gu et al., 2008a), the green construction assessment method (Tam et al., 2004), EI99 and the construction pollution index (Chen et al., 2000). Although the panel method is straightforward to use, the weighting factors may differ considerably between the individuals in a panel due to the subjective nature of value choices (Myllyviita et al., 2014; Oztas and Tanacan, 2014). Furthermore, the panel size is not always sufficient to ensure the representativeness of the survey results (Itsubo et al., 2012).

These weighting approaches have strengths and weaknesses, and they each work well in different scenarios. The monetization approach is the best method when objectively measuring public concerns; the distance-to-target approach is recommended to governments for policy development; and the panel method has outstanding performance when the suggestions of field experts are highly valued. Three weighting approaches measure the significances of various categories from different perceptivities. In the new model, either weighting method is available to express building EHP as a single value: the environmental and health performance value (EHPV). Users are recommended to select an appropriate weighting approach according to their specific assessment goals. It is noted that the weighting factor values in three weighting approaches should be

identified according to the assessed building location for the significances of categories in different regions are quite different. If apply the monetization method, the local green taxes are suggested to be used to reflect the residence concerns; if apply the distance-to-target method, the local governmental policies are adopted; and if apply the panel method, expert opinions will be offered according to the local environmental concern levels and economic conditions.

3.4 Interpretation

Following the above steps, the EHP of a building is assessed. The calculation results better elucidate the construction process while identifying major impact categories and critical burdening substances. Effective improvement suggestions are proposed to guide the sustainable development of green buildings. Moreover, sensitivity analyses can be performed for designers to determine which building components consistently have the largest impacts (Basbagill et al., 2013).

4. Application

4.1 Basic information

Nine residential buildings in Jiangsu, China, under the same geographical conditions by the same contractor and with the same level of insulation are taken as cases. These buildings are made of the three most common structural types among Chinese residences (a brick masonry structure for low-rise residences, a frame structure for mid-rise residences and a frame shear wall structure for high-rise residences), rendering the comparable results meaningful in guiding residential design. The evaluation results help to demonstrate how impacts are distributed throughout the pre-occupancy phase and to determine which building components and materials are critical in terms of building

performance.

Following the framework of the newly developed model, the building cases are divided into 11 unit processes (see Fig. 4) based on the engineering quantities derived from the engineering drawings. The engineering quotas vary according to local geographic conditions, building industry development statuses, and construction management levels. We use the *Table of Jiangsu Province Construction and Decoration Engineering Cost* (Department of Housing and Urban-Rural Development [DOHURD] of Jiangsu, 2004) in the case studies because it provides relatively new and complete consumption data for all sources in each unit process. Consumptions of the 9 cases are transformed into environmental profiles, and Table 4 shows partial the profiles.

In the weighting step, WTP is used to objectively quantify the building EHP from an economic perspective. In the ecological damage and resource depletion assessment, the monetary weighting factors are proposed based on the concept of green taxes (Wu et al., 2005), and we applied the values from Cao et al. (2015) because they were updated according to the recent green tax rates and the unit costs of pollutant disposal in China. For the health damage, VSL is selected to transform DALY into the damage value on a monetary basis. Currently, the VSL of \$7.9 million (in 2008 dollars) as recommended by the U.S. Environmental Protection Agency (EPA) is widely used to value reduced mortality for programs and policies (U.S. EPA, 2010). Due to the absence of similar studies in China, this value is adopted and adjusted (considering composite inflation rate from 2008 to 2015, purchasing power parity between the U.S. and China, and purchasing power parity between the country of China and Jiangsu Province) to reflect the social and economic differences between China and the U.S., taking the calculation steps from Li et al. (2010) as a reference. Finally, the value of a

statistical life year (VSLY) of Jiangsu residences is $4.42E+05$ yuan, as calculated by the approach proposed by Pearce (2000).

4.2 Results and analysis

Comparison across safeguard areas: Fig. 5 shows that the average EHPV of a residence is 21.57 yuan, quantifying the damage caused by related activities per 1 m² in the pre-occupancy phase. The average assessment values of ecological damage, resource depletion and health damage categories are 12.34, 2.10 and 7.13 yuan, respectively. Ecological damage composes 57.23% of EHPV, thus making the greatest contribution followed by health damage (33.05%). Building construction goes against sustainable development and seriously harms ecosystem and human wellbeing.

Fig. 5. Average assessment values of the three safeguard areas (unit: m²).

Comparison across categories: Fig. 6 shows the proportion distribution of categories. Global warming accounts for the largest portion (35.03%) and far exceeds the values of the others. This is due to the fact that approximately 80% of electricity in China is produced from thermal power (National Bureau of Statistics of China,

2011), resulting in considerable pollutant generation and a dramatic increase in GHG emissions (Yang and Chen, 2014). Thus, energy supply structure adjustments and clean energy development activities will improve building EHP levels. In addition to global warming, the impacts of circulatory effect (31.63%), eutrophication (15.32%), acidification (7.29%), and water resource depletion (7.04%) are also large. With increasingly more ongoing construction projects in China, more attention should be paid to environmental issues such as global warming and eutrophication as well as health issues such as the circulatory effect.

Fig. 6. Proportional distribution of categories

Comparison across structure types: Fig. 7 compares the EHP of the three building structures. The average EHPV is 29.65 yuan for the frame shear wall structure, 21.20 yuan for the frame structure, and 13.85 yuan for the brick masonry structure. In general, the frame shear wall building performs 0.40 times worse than the

framed building and performs 1.14 times worse than the brick masonry building. This difference is quite significant, and structure type is a major factor for building EHP. From the perspective of environmental protection, brick masonry structures are more suitable for residences.

Fig. 7. Average EHPV of the three building structures (unit: m^2)

Comparison across unit processes: The first three major unit processes of each structure type are shown in Fig. 8. For frame shear wall residences, the major unit processes include reinforced concrete (35.62%), foundation work (29.70%) and earthwork (19.02%). For frame structure residences, the major unit processes include reinforced concrete (50.70%), masonry work (25.89%) and earthwork (19.02%). For brick masonry residences, the major unit processes include reinforced concrete (41.65%), earthwork (33.98%) and masonry work (14.70%). On one hand, the major unit processes for the three structures vary in terms of construction techniques, building materials and serviced machine equipment. On the other hand, most building

impacts are derived from 3 unit processes of the total of 11; these 3 processes account for a cumulative percentage of more than 80%. Thus, specific environmentally friendly measures in these unit processes will effectively improve building performance levels.

Fig. 8. First three major unit processes of the three building structures

Comparison across burden substances: The proportional distribution of some main burden substances is shown in Fig. 9. For frame shear wall structure residences, the first three burden substances are diesel, concrete and water. For frame structure residences, the first three burden substances are diesel, concrete and aerated concrete block. For brick masonry structure residences, the first three burden substances are concrete, diesel and autoclaved fly ash brick. Concrete and diesel are major burden substances in the pre-occupancy phase for all three building structure types. Thus, production technology improvements, usage restrictions, and alternative material substitutions are suggested to mitigate damage. The main burden substances are also

affected by the structure type: the EHPV of aerated concrete blocks in frame structure buildings is considerably higher than that in the other two structures, and the EHPV of autoclaved fly ash brick in brick masonry structure buildings is also higher for a larger associated consumption.

Fig. 9. EHPV proportional distribution of some burden substances

5. Conclusions

This paper introduces an integrated building assessment framework to present how impacts in pre-occupancy phase are distributed throughout building elements. The new model follows the LCA framework (i.e., goal & scope definition, LCI analysis, life cycle impact assessment and interpretation) and integrates the inventory

analysis, classification, characterization and weighting steps of BEPAS and BHIAS. The evaluation boundary of this system is the pre-occupancy phase, and the EHP is classified into several categories of three safeguard areas: ecosystems, natural resources and human health. Engineering drawings and quotas are used to estimate the consumption data and to analyze the inventories, making it possible to assess impacts immediately after the design drawings are completed and to guide improvement before construction. Three common weighting approaches (i.e., monetization, distance-to-target and the panel method) along with their advantages and shortcomings are introduced. The newly developed assessment model is expected to pre-assess building performance and identify major impact factors.

Nine residential buildings with three different structures are taken as case studies to test the operation of the proposed model in practical projects. We draw the following conclusions: (1) construction damages the ecosystem the most, and the assessment value of global warming is the highest of all of the categories; (2) the structure type is a significant factor affecting the performance of residential buildings, and the frame shear wall structure is the least environmentally friendly and health friendly, followed by the frame structure and the brick masonry structure; and (3) major unit processes and burden substances are affected by the structure type. For all three structures, reinforced concrete and earthwork are major unit processes, and concrete and diesel are critical burden substances.

The model proposed in this paper is not yet fully developed, and further

improvements are still being made. First, some environmental factors (e.g., indoor climate and traffic) are not considered in the model, as LCA focuses on environmental damages occurring over a rather large scale (e.g., ecosystems). Second, this research quantifies the EHP in pre-occupancy phase instead of the whole life cycle, which decreases the practical value of assessment results to some extent. EHPs in more phases are suggested to be assessed in the future works to help guide decision making and improvements in the design phase. Additionally, due to a lack of available epidemiological data in China, we focus only on health damages caused by air pollutants and thus neglect the effects caused by pollutants in the water and soil. Therefore, we underestimate the total impacts of buildings. Because the integrated model presented in this paper is an open system, it will be improved with the progress of epidemiologic study and LCA research in China.

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